Biofouling
Vol. 25, No. 7, October 2009, 645–655

The role of containerships as transfer mechanisms of marine biofouling species

Ian C. Davidson[a]*, Christopher W. Brown[b], Mark D. Sytsma[a] and Gregory M. Ruiz[a,c]

[a]*Aquatic Bioinvasions Research and Policy Institute, Environmental Sciences and Management, PO Box 751, Portland State University, Portland, Oregon 97207-0751, USA;* [b]*Smithsonian Environmental Research Center, Marine Invasions Research Laboratory, Romberg Tiburon Center for Environmental Studies, 3152 Paradise Drive, Tiburon, California 94920, USA;* [c]*Smithsonian Environmental Research Center, Marine Invasions Research Laboratory, PO Box 28, Edgewater, Maryland 21037, USA*

(*Received 19 March 2009; final version received 14 May 2009*)

Fouling of ships is an important historical and enduring transfer mechanism of marine nonindigenous species (NIS). Although containerships have risen to the forefront of global maritime shipping since the 1950s, few studies have directly sampled fouling communities on their submerged surfaces, and little is known about differences in the fouling characteristics among commercial ship types. Twenty-two in-service containerships at the Port of Oakland (San Francisco Bay, California) were sampled to test the hypothesis that the extent and taxonomic richness of fouling would be low on this type of ship, resulting from relatively fast speeds and short port durations. The data showed that the extent of macroorganisms (invertebrates and algae) was indeed low, especially across the large surface areas of the hull. Less than 1% of the exposed hull was colonized for all apart from one vessel. These ships had submerged surface areas of >7000 m^2, and fouling coverage on this area was estimated to be <17 m^2 per vessel, with zero biota detected on the hulls of many vessels. The outlying smaller vessel (4465 m^2) had an estimated coverage of 90% on the hull and also differed substantially from the other ships in terms of its recent voyage history, shorter voyage range and slower speeds. Despite the low extent of fouling, taxonomic richness was high among vessels. Consistent with recent studies, a wide range of organisms were concentrated at more protected and heterogeneous (non-hull) niche areas, including rudders, stern tubes and intake gratings. Green algae and barnacles were most frequently sampled among vessels, but hydroids, bryozoans, bivalves and ascidians were also recorded. One vessel had 20 different species in its fouling assemblage, including non-native species (already established in San Francisco Bay) and mobile species that were not detected in visual surveys. In contrast to other studies, dry dock block areas did not support many organisms, despite little antifouling deterrence in some cases. Comparisons with previous studies suggest that the accumulation of fouling on containerships may be lower than on other ship types (eg bulkers and general cargo vessels), but more data are needed to determine the hierarchy of factors contributing to differences in the extent of macrofouling and non-native species vector risks within the commercial fleet.

Keywords: containerships; biofouling; fouling; hulls; species introductions; vectors

Introduction

Efforts to reduce the environmental impacts of transportation have prompted several initiatives to promote 'greener' maritime shipping. These include reducing emissions from ships that impact air quality (International Maritime Organization 1998; Endresen et al. 2003), and enforcing speed restrictions near ports to prevent whale collisions (Laist et al. 2001; Ward-Geiger 2005). A major initiative embraced by many countries and the International Maritime Organization (IMO) was the establishment of ballast water management strategies to reduce the risk of invasions by nonindigenous species (NIS) by decreasing the organisms (propagule supply) discharged in ballast water (Endresen et al. 2004; International Maritime Organization 2004a; Minton et al. 2005).

Biofouling of ships' hulls is another potent transfer mechanism (vector) for coastal invasions, but it has received less attention globally, despite being a centuries-old mechanism of species introductions (Carlton 1985; Minchin and Gollasch 2003). Several studies of historical invasion patterns encompassing a wide geographical range and different spatial scales have shown that fouling has played an important and sometimes dominant role in the distribution of NIS (Ruiz et al. 2000; Eldredge and Carlton 2002; Fofonoff et al. 2003; Hewitt et al. 2004; Gollasch 2006). Recent fouling-mediated introductions also highlight the enduring nature and current operation of this vector (Hewitt et al. 2009).

The number and magnitude of hull-mediated introductions have doubtlessly varied over time, particularly in relation to shifts in maritime shipping.

*Corresponding author. Email: idavidso@pdx.edu

ISSN 0892-7014 print/ISSN 1029-2454 online

DOI: 10.1080/08927010903046268
http://www.informaworld.com

Transformations from sail to self-propulsion, wooden to steel hulls, and the evolution of antifouling (AF) applications throughout maritime history have each contributed to changes in organism settlement, retention and transfers on vessel hulls (Visscher 1928; Carlton 1985; Nehring 2001; Callow and Callow 2002). More recently, modern commercial ships have been specialized to handle specific freight with particular cargo handling and port terminal requirements.

The rise of containerships in the commercial fleet since containerization and inter-modal shipping that began in the 1950s has revolutionized maritime transport and trade (Vigarie 1999). Containerships replaced a large proportion of the bulk carrier trade because standardization of cargo (using 20 ft equivalent units or TEUs) brought new efficiency, speed and profitability. The consequence of this transformation for biofouling is linked to the emergence of faster vessels with shorter port durations, two factors that influence the settlement, accumulation and retention of organisms on external vessel surfaces. Thus, different ship types may be expected to differ in NIS vector potential.

The effect of different commercial ship types on the transfer of fouling species has gone largely unnoticed, however. Indeed, fouling data from modern, in-service, commercial ships are quite limited, despite a recent resurgence of interest in the topic (Gollasch 2002; Godwin 2003; Coutts and Taylor 2004; Farrapeira et al. 2007; Mineur et al. 2007). The aim of the present study was to examine fouling assemblages on the hulls and underwater surfaces of in-service containerships at port (ie not in dry-dock), hypothesizing that containership 'behavior' should result in a low extent of fouling and taxonomically poor assemblages. Specifically, the following were investigated: (1) the extent and broad composition of fouling and its distribution among hull locations on containerships; (2) the species richness on a subset of these ships; (3) how fouling was related to vessel characteristics (surface area, speed, port duration) and recent operational history (voyage routes, duration since last dry dock). The results for containerships in this study were also compared to fouling on other ships reported in the literature.

Methods

Sampling

Sampling was conducted on the hulls and underwater surfaces of commercial ships at dockside in the Port of Oakland on two separate 2-week periods, using divers in April 2004 and a remotely operated vehicle (ROV) in May 2006. The Port of Oakland is situated within San Francisco Bay and is the fourth busiest container port in the US (Port of Oakland 2007), receiving more than 1900 vessel calls annually (Falkner et al. 2007). Vessels were selected haphazardly based upon the arrival, docking schedule and permission of candidate vessels. Vessel participation was dependent upon safe access to submerged surfaces which usually required temporary shut-down of water intake, cathodic protection and propeller rotation. Both visual survey methods produced comparable (recorded) video footage of the submerged surfaces of the ships. Dive surveys consisted of a SCUBA diver operating a video camera and a boat-based group that were connected *via* video and verbal communications throughout each survey. Direct, two-way and continuous communication lines between the diver and the surface team allowed for detailed notes, discussion and *in situ* analyses by the entire survey team. Similarly, the ROV was operated from dockside where a 3-person team operated the vehicle, took detailed notes and tended the umbilical. The vehicle used was a 31.75 kg Mini-Rover MKII with a dome-encased 420-Line/0.5-Lux camera and 304.8m (1000 ft) umbilical.

The underwater surfaces examined for all vessels included the hull, rudder, propeller and stern tube. Rudder surveys involved transects of the perimeter edges, articulations and flat surfaces. Propeller surveys included inspection of the forward and aft faces and edges of propeller blades, as well as the center (cone) where hydrodynamic turbulence is less than at propeller extremities (Coutts and Taylor 2004). Stern tubes were examined with transects across the top and bottom surfaces and detailed inspection of the articulation between stern tube and propeller. The hulls were examined using vertical transects of the sides of the vessel below the waterline and horizontal transects of the flat bottoms of the ships. Dry dock blocking areas were incorporated into the flat bottom hull sampling. These areas are often conspicuous, rectangular patches of the hull where 'new' AF paint is lacking; the blocks that support the ship during dry docking can prevent paint application to these areas, unless the blocks are moved. In addition, the bulbous bow, bow thruster grating, and intake gratings (including sea-chests) of several vessels were examined when possible.

The visual surveys provided a presence/absence matrix of broad taxonomic groups of fouling organisms at each hull location. The extent (area covered) of fouling within flat-bottom hull transects was estimated by measuring the area sampled and the percentage of that area occupied by fouling organisms. The number of dry dock blocks and their area were also estimated. Coarse taxonomic identification (broad functional groups) using video footage was carried out for all vessels, and finer taxonomic resolution was possible from a subset of the vessels examined by divers from which biological samples were collected from each vessel location. In addition to finer taxonomic data, this subset of ships provided data on whether mobile species, not visible or conspicuous in the image analysis, were present within fouling matrices that were encountered during visual surveys. The biological samples were collected by scraping fouling organisms into individually numbered re-sealable (zipped) bags and returning them to the surface where they were examined for signs of life and then preserved in labeled containers. Specimens were identified to the lowest possible taxonomic level, using taxonomic experts for confirmation.

In addition to biological data for each vessel sampled, characteristics (specifications) and recent operational history of vessels were collected using a questionnaire that was completed by the captain, chief mate and/or chief engineer of each vessel. The previous dry docking date was nearly always provided to the month, but when only year was provided, the midpoint of that year was used to calculate the duration since docking. Vessel dimensions were also noted and used for calculating wetted surface area (WSA) of each vessel. WSA is an estimate of the submerged surface area of ships or the colonizable space available to marine organisms (fouling species) on the surfaces of ships. WSA is analogous to ballast water volumes for the ballast vector and was calculated using vessel length, breadth, draft and published coefficients (Lewis 1988) for different commercial ship types as described by Van Maanen and Van Oossanen (1988).

Data analysis

Vessel characteristics, including vessel age, typical speed, port duration, WSA, paint type and duration out of dry dock were tabulated and used for subsequent comparisons. Voyage itineraries were also tabulated based on the ports visited on the ships' regular service. Tests for differences in fouling composition between sampling events and voyage routes were performed using analysis of similarities (ANOSIM) in the PRIMER program (Primer-E Ltd, Plymouth). ANOSIM uses similarity matrices to test for differences between groups of samples (ships in this case), usually providing an r-value between 0 (no segregation) and 1 (completely separate groups). The RELATE function in the same program was used to examine whether period-since-last-dry-dock and WSA were related to similarity/dissimilarity among vessels. Likewise, this routine produces a statistic that approaches 1 or 0 indicating whether similarity of a factor among vessels and assemblage similarity are entirely related or not at all related, respectively (Clarke and Gorley 2001). Cluster analysis and dendrograms were used to compare similarities among vessel locations. Differences in the number of taxa among hull locations were tested using the non-parametric Kruskal–Wallis and Mann–Whitney U tests in SPSS v13. An analysis of covariance (ANCOVA) tested for differences between ships from this and another study (Coutts 1999) using the variable 'period-since-last-dry-dock' as the covariate. Coutts' (1999) data from a study conducted in Tasmania was used for comparison because it was similar in terms of methodology and data presentation.

Results

Vessel characteristics

Nine vessels were sampled using divers in 2004 and a further 13 using a ROV in 2006 (22 in total). There were numerous characteristics that the vessels had in common (Table 1), including typical port duration (generally <24 h) and typical operating speed (generally 21–25 knots). There were also notable differences among ships, such as the large range in WSA between the largest and smallest ships sampled (9750 m^2). One vessel (r10) was an outlier in terms of typical speed, generally traveling at considerably slower speeds (15 knots) compared to all other ships sampled (Table 1). AF paints varied among vessels with two vessels operating with a mixed tin-based paint in 2004, but all other vessels had tin-free paint. Vessel operators reported that copper was the main active ingredient of self-polishing copolymer (SPC) paint systems. Three vessels reported using a silicone-based fouling-release coating, which does not use a biocidal agent to prevent fouling accumulation. There was substantial variation among vessels in terms of age (4 months–33 years) and period since last dry docking (2 months–5 years).

Vessel itineraries (voyage routes) fitted four different models of maritime transportation: pendulum, round-the-world, port-to-port and coastal short-sea (see Rodrigue et al. 2006). A majority of vessels followed pendulum transport models (Table 1) whereby a ship's transoceanic voyages were interspersed with coastwise port calls on the opposing sides of the same ocean (the Pacific in this instance). Of the 17 vessels that undertook pendulum voyages, 13 traveled between US and Asian mainland ports while 4 traveled between the US mainland and oceanic islands (Hawaii, Guam, and Saipan). Two vessels had round-the-world itineraries incorporating port visits in Asia, Europe, the East Coast and the West Coast of the US, with passages through the Suez and Panama Canals. Two other vessels traveled between Oakland and Hawaii (port-to-port model) with occasional visits to Tacoma in Puget Sound. One vessel (r10) traveled coastally among ports in Mexico, California, Washington and British Columbia, although had previously worked

Table 1. Characteristics and recent operational history of 22 containerships sampled in Oakland.

Vessel	Survey type	Estimated WSA (m^2)	Age at time of survey (years)	Typical speed (knots)	Typical port duration (hours)	Duration since last dry dock	Antifouling ingredient	Voyage model
d1	Diver	11,722	–	24	< 24	–	–	Pendulum
d2	Diver	13,096	9	24	< 24	57	TBT	Pendulum
d3	Diver	13,129	3	24	< 24	33	–	Pendulum
d4	Diver	13,179	3	24	< 24	33	–	Pendulum
d5	Diver	13,096	9	24	< 24	57	TBT	Pendulum
d6	Diver	7,117	33	21	24–48	8	Cu	Pendulum[a]
d7	Diver	8,292	24	21	8–36	11	Cu	Pendulum[a]
d8	Diver	10,505	24	24	9–36	3	Cu	Pendulum[a]
d9	Diver	10,825	11	24	< 24	12	–	Pendulum
r1	ROV	13,096	11	24	< 24	16	Silicone	Pendulum
r2	ROV	13,104	10	22	18	12	Silicone	Pendulum
r3	ROV	12,820	0.3	25	24	4	Cu	Pendulum
r4	ROV	13,498	5	24	24	60	Cu	Pendulum
r5	ROV	12,142	15	22	12–24	23	Cu	Round-the-world
r6	ROV	8,292	26	21	8–36	13	Cu	Pendulum[a]
r7	ROV	8,584	34	21	36	23	Cu	Port-to-port
r8	ROV	12,161	14	23	12–16	24	Cu	Round-the-world
r9	ROV	12,077	11	23	12–24	14	Silicone	Pendulum
r10	ROV	4,465	–	15	12–24	26	–	Short-sea
r11	ROV	9,797	24	22	12–36	22	–	Port-to-port
r12	ROV	14,215	3	24	12	2	Cu	Pendulum
r13	ROV	11,857	9	21	12	59	Cu	Pendulum

The following data were provided by ship operators: vessel age, usual speed and port duration, date of last dry docking, antifouling paint used, and port itinerary for recent voyages. WSA was estimated from vessel dimensions and a voyage model was assigned to ships based on their itineraries (see text).

ROV, remotely operated vehicle; –, information unavailable; TBT, mixed coverage of tributyl tin-based and tin-free paint because of difficulties in covering the original TBT paint with a new coating; Cu, copper-based antifouling paint; silicone, biocide-free foul release coating.

[a]Pendulum voyage model with routes between the US mainland and oceanic islands. All other ships with pendulum routes traveled between mainland Asia and the West Coast (see text).

among the Caribbean islands prior to transferring to Pacific coastal trade.

Biofouling extent and richness

Fouling organisms were observed on 20 of the 22 vessels sampled. Macroscopic fouling was observed most frequently on the rudders, followed by stern tubes and bow thruster gratings of vessels (Figure 1). Although biota was recorded on the hull surfaces (sides, flat bottom and/or dock block areas) of a majority of vessels (60%), the extent of fouling was generally low and most hull surface area was free of macroorganisms. On the flat bottoms of hulls, where transects were used to estimate the extent of fouling, there was little fouling detected either within or outside of dock block areas (Table 2). Only seven vessels had any fouling on the flat-bottom hull surface and only three of these had a cumulative fouling extent > 100 cm^2, despite many dock block areas substantially lacking AF paint. Only 27 of 339 dock block areas encountered had organisms within them and all but one vessel had $< 1\%$ of its available surface area (WSA) occupied by fouling organisms. The one exception was vessel r10, where 90% of a 50 m^2 transect was covered with encrusting organisms, obscuring visual differences between dock block and non-dock block areas. The proportion of this vessel's extensive fouling that was alive could not be determined from video footage.

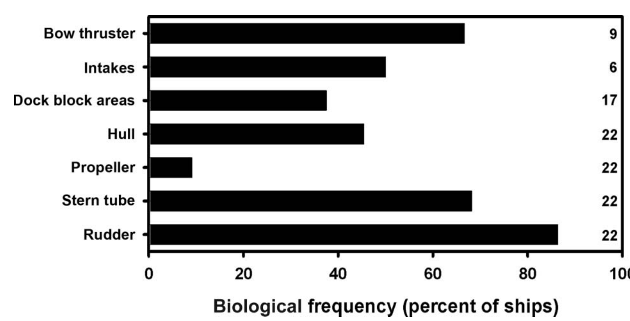

Figure 1. Differences in biofouling among submerged ship locations. The frequency of fouling, measured as the percentage of vessels examined, is shown for seven different vessel locations. The values at the end of each bar represent the number of vessels examined for that location. Note that 60% of all vessels had fouling on hull surfaces and dock block areas combined.

Table 2. Extent of biofouling on flat-bottom hull surfaces of containerships.

Vessel	Vessel length (m)	Number of dock blocks surveyed	Number of dock blocks with organisms	Biofouling extent within flat bottom area surveyed (m^2)	Estimated percent cover of biofouling within flat-bottom transect
d1	288.3	33	0	0.00	0
d2	276.3	0[a]	0	0.00	0
d3	277.0	0[a]	0	0.00	0
d4	277.3	0[a]	0	0.00	0
d5	276.3	27	0	0.00	0
d6	247.9	48	1	0.02	<0.5
d7	272.3	55	8	0.08	<0.5
d8	276.5	15	0	0.00	0
d9	186.6	0[a]	0	0.00	0
r1	276.3	13	2	2.80	<1
r2	276.3	26	0	0.00	0
r3	283.8	14	0	0.00	0
r4	284.7	0[a]	0	0.00	0
r5	294.0	8	1	0.01	<0.5
r6	162.9	12	1	0.40	<0.5
r7	247.6	14	14	6.40	<2
r8	294.0	20	0	0.00	0
r9	292.2	12	0	0.00	0
r10	162.9	0[b]	n/a	45.00	90
r11	262.1	n/a	n/a	0.00	0
r12	299.9	20	0	0.00	0
r13	292.1	22	0	0.00	0

Vessel length, number of dock blocks encountered during the hull-bottom transect, number of dock blocks with biofouling and estimates of cover are reported for each ship. For some vessels, biofouling was recorded on the sides and stern of the hull but this table reports block and non-dock block biofouling on the undersides (flat-bottom) of hulls only.
n/a, not applicable.
[a]No dock blocks were encountered or evident despite an extensive search.
[b]Dock blocks were not identified because biofouling coverage made dock block and non-dock block areas indistinguishable.

There were 10 broad taxonomic groups encountered among all vessels (Table 3). Green macroalgae, primarily species of the order Ulvales, and acorn barnacles were the most commonly occurring functional groups. Tubeworms and hydroids were also quite prevalent among vessels, whereas the remaining seven taxonomic groups occurred on <25% of the vessels examined. Among all ships, several taxa occurred in patchy aggregations (eg clumps of barnacles), but individuals within four groups (brown and red algae, ascidians and goose-neck barnacles) were recorded in isolation only. Rudders also had the highest number of taxa on average compared to other submerged locations of ships (Figure 2a). A similarity dendrogram revealed three clusters of fouling locations: (1) dock block areas and propellers, (2) rudders and hulls, and (3) stern tubes, bow thrusters and intake gratings (Figure 2b). Propellers and dock block areas were notable for the lack of fouling organisms encountered.

A total of 34 species (or unique taxa) were recorded among the subset of five ships from which samples were collected (Table 4). Species richness per ship ranged between 6 and 20. The increase in taxa compared to visual surveys resulted from (1) better taxonomic resolution of organisms detected previously in visual surveys and (2) an increase in the detection of taxa, particularly mobile species within matrices of fouling that went undetected on video. Additionally, finer resolution of taxa provided some biogeographical insight; the barnacle *Conchoderma* sp., is an oceanic species that most likely recruited to ships in the open ocean. A majority of taxa were from coastal habitats, however, and many included species with resident populations within San Francisco Bay. For those taxa identified sufficiently, no NIS that is not already established within the Bay was detected. Among the most abundant organisms were mussels (*Mytilus* sp.), which ranged in size from 3 to 49 mm across three vessels, and size distributions differed significantly among ships (Kruskal–Wallis test, $\chi^2 = 123.9$, d.f. $= 2$, $p < 0.001$).

Analysis of the composition of fouling (ANOSIM tests) revealed no significant differences among vessels in terms of voyage routes (pendulum *vs* other) and sampling occasions (2004 *vs* 2006; ANOSIM, all $r < 0.127$, all $p > 0.1$). There were also no significant relationships between WSA and taxa richness or assemblage similarity. Taxa accumulation increased significantly with duration since last dry-docking ($r^2 = 0.401$, $p < 0.01$). RELATE tests also revealed that assemblage similarities among vessels were related

Table 3. Occurrence of broad taxonomic groups on ships.

Vessel	d1	d2	d3	d4	d5	d6	d7	d8	d9	r1	r2	r3	r4	r5	r6	r7	r8	r9	r10	r11	r12	r13
Green algae	−	+	+	−	+	+	+	−	−	+	+	+	+	+	+	+	+	+	+	+	−	+
Red algae	−	+	−	−	−	−	+	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−
Brown algae	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−
Acorn barnacles	+	+	+	−	+	−	+	+	+	+	+	−	+	+	−	+	+	+	+	+	−	+
Goose-neck barnacles	−	+	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−	−	−	+
Tubeworms	−	+	−	−	+	−	+	−	+	+	−	−	+	+	−	+	−	−	+	−	−	+
Hydroids	−	+	+	−	+	−	−	−	−	−	+	−	−	−	+	+	−	+	+	−	−	+
Bryozoans	−	+	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	+	+	−	+
Mussels	−	+	−	−	+	−	−	−	+	−	−	−	−	−	−	−	−	−	−	−	−	+
Ascidians	−	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

The taxa recorded on each of 22 ships after visual surveys are shown.
+, presence; −, absence.

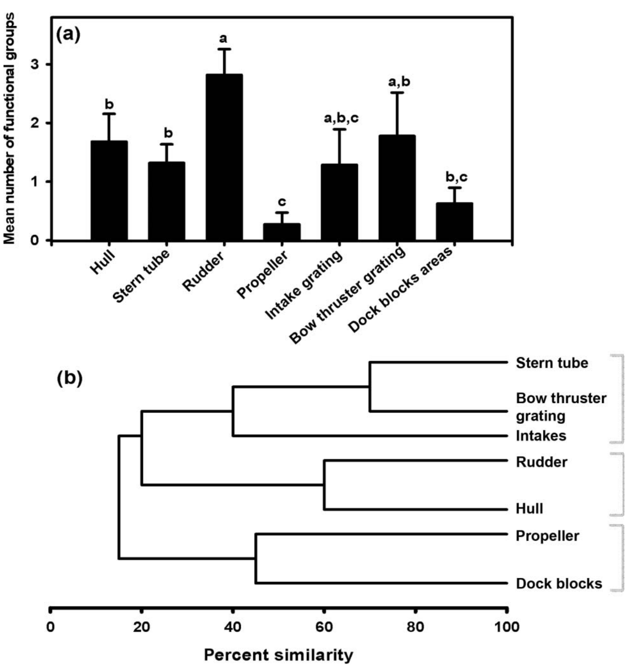

Figure 2. Richness and composition among submerged ship locations. (a) The mean number of functional groups (±SE) for each vessel location is plotted. There was a significant difference between all locations (Kruskal–Wallis test, $\chi^2 = 29.8$, $p < 0.001$). Letters above the bars indicate significant differences between locations based on pair-wise Mann–Whitney U tests ($p < 0.05$). (b) Similarity dendrogram of hull locations based on Bray–Curtis similarity of presence/absence of taxa.

to duration since last dry dock (test statistic = 0.323, $p < 0.005$).

Data from the present study and Tasmania (Coutts 1999) were used to plot duration since last dry dock against functional group richness for 42 vessels (21 from each study) for which data were available (Figure 3). Ships from Tasmania were mainly bulkers and general cargo vessels. As recorded in Oakland, there was a significant positive linear relationship between dry dock duration and functional group richness for Tasmanian ships ($r^2 = 0.291$, $p < 0.02$). There were five Oakland ships and one from Tasmania that had fewer than four functional groups on their submerged surfaces despite >21 months duration since the previous dry-docking (Figure 3). An ANCOVA revealed no significant difference between the studies in the accumulation of functional groups on ships ($F = 0.304$, $p > 0.05$), despite the appearance of lower richness over time for Oakland vessels. In contrast, Tasmanian ships had a notably higher extent (abundance) of fouling compared to Oakland ships. Coutts (1999) recorded (1) almost 100% fouling cover in some dock block areas, (2) >25% average cover in samples for seven macroalgal species on some ships, and (3) estimated population sizes of several thousand individuals each for five barnacle species. Percentage cover and abundance of fouling on containerships in Oakland did not approach these values.

Discussion

Biofouling extent and distribution on hulls

Potential differences in the extent and diversity of fouling among ship types within the commercial fleet have been largely ignored to date. Yet, these are important risk factors for evaluating and predicting invasions among ports. The current state of analyses for hull fouling contrasts with that for ships' ballast water, where significant variation has been documented among different ship types in the frequency, volume, and biotic content of water discharged (Verling et al. 2005).

Containerships arriving in Oakland did not have an extensive coverage of fouling on their submerged surfaces. Relative to other ship types, containerships generally spend <12 h in port, spend a very high proportion of their time underway, and travel at high speeds while in transit. For example, containerships

Table 4. Species richness on containerships.

Taxa recorded from sample collections	Vessels d2	d3	d5	d7	d9
Green algae	+	+	+	+	−
Red algae	+	−	−	+	−
Annelida					
Polychaeta					
Hydroides sp.	−	−	+	−	−
Nereidae sp.	−	−	+	−	−
Nereis neoneanthes	−	−	+	−	−
Nicolea sp.	+	−	−	−	−
Polynoidae sp.	−	−	−	+	−
Phyllodocidae sp.	−	−	−	+	−
Sylidae sp.	−	−	−	−	+
Bryozoa					
Unidentified bryozoan	+	−	−	−	−
Chordata					
Tunicata					
Styela sp.	+	−	−	−	−
Cnidaria					
Hydrozoa					
Clytia sp.	−	+	−	−	−
Obelia dichotoma	+	−	+	−	−
Tubulariidae sp.	+	−	−	−	−
Arthropoda					
Crustacea					
Cirripedia					
Amphibalanus amphitrite[a]	+	+	−	+	−
Balanus sp.	+	−	−	−	+
Chthamalidae sp.	+	−	+	−	−
Conchoderma auritum	+	−	−	−	−
Megabalanus sp.	+	+	+	−	−
Pollicipes polymerus	+	−	−	−	−
Amphipoda					
Monocorophium acherusicum	+	−	−	+	−
Caprella equilibra	+	−	+	−	−
Hyalidae sp. (juvenile)	−	+	−	−	−
Jassa marmorata	+	−	+	−	−
Jassa sp. (juvenile)	+	−	−	−	−
Corophidae sp. (juvenile)	−	−	−	+	−
Ptilohyale sp.	−	−	−	−	+
Unidentified amphipods	−	+	−	−	+
Copepoda					
Paralaophonte sp.	−	−	+	−	−
Isopoda					
Unidentified isopod	−	−	−	+	−
Mollusca					
Bivalvia					
Mytilus sp.	+	−	+	−	+
Unidentified bivalve	−	−	−	−	+
Nemertea	+	−	+	−	−
Unidentified nemertean	+	−	+	−	−
Porifera					
Halichondria sp.	+	−	−	−	−

The unique taxa identified from biofouling collections from five ships are shown.
+, presence; −, absence.
[a]*Amphibalanus* used instead of *Balanus* (see Carlton and Newman 2009).

are reported to spend >30% of the time that bulkers spend on cargo operations and can travel up to 50% faster than bulkers (Kite-Powell and Hoagland 2002; Entec International 2005). Each of these factors is expected to prevent extensive accumulation of fouling and reduce the risk of species transfers (per ship) on this external vector. Contrary to predictions, however, taxonomic richness among the 22 ships sampled was unexpectedly high, with a wide range of taxa occurring on some vessels despite a limited extent of fouling accumulation.

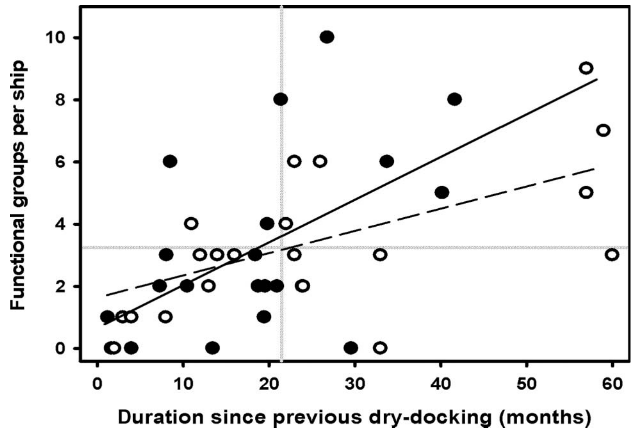

Figure 3. Relationships between duration since last dry dock and number of functional groups recorded on ships. Data are from the present study (white symbols, containerships) and Tasmania (Coutts 1999; black symbols, mainly bulkers and general cargo vessels). There were significant linear relationships for Oakland ships ($r^2 = 0.401$, $p < 0.01$; dashed line) and Tasmanian ships ($r^2 = 0.291$, $p < 0.02$; solid line), but no significant difference in accumulation of taxa over time between both studies (ANCOVA, $F = 0.304$, $p > 0.05$). Gray lines represent the mean value for both axes.

The results indicated that the arrival of most containerships brings biota associated with their submerged surfaces. This is consistent with other recent analyses where most ships, including containerships, were reported to have some macrofouling (Gollasch 2002; Coutts and Taylor 2004; Mineur et al. 2007). It was also found that fouling organisms were not evenly distributed across the submerged surfaces of in-service vessels; heterogeneous 'niche' areas are challenging for the effectiveness of AF paints and susceptible to fouling accumulation (Coutts and Taylor 2004). These hotspot locations often include recesses on ships' submerged surfaces, allowing a wide range of organisms to colonize even while most of the more exposed, flat-bottom hull surface remains free of biota.

The extent of fouling was generally low because painted and unpainted hull surfaces, those spaces subjected to laminar water flow, were notably free of fouling. Unlike commercial ships in New Zealand (Coutts and Taylor 2004), dock block areas and propellers were the least fouled locations across all vessels sampled in Oakland. Containerships in New Zealand ($n = 17$) had 30% and 20% fouling cover of dock blocks and hull areas (outside dock block areas), respectively. Propellers among all ship types in New Zealand had up to 90% of their surfaces fouled, primarily with fine and filamentous algae. This contrasted with Oakland arrivals where a majority of ships were devoid of fouling at these locations and when organisms were encountered, only small isolated patches were recorded. All New Zealand ships had long periods since dry-docking ($\sim$36 months), which may explain the differences between the two studies, while containerships in New Zealand tended to have less fouling than other ship types in that study (a total of 30 ships were sampled by Coutts and Taylor (2004)). The surprisingly low number of organisms encountered in dock block areas in Oakland was especially striking because of the poor condition of paint (some with apparent patches of bare metal) prevalent in these areas on several ships. Dock block areas can provide tens to hundreds of square meters of colonizable surface area without effective AF (in this study, vessel r13 reported 416 dock block areas). Only 8% of $>$300 dock block areas surveyed in this study had any fouling present, and none had the extensive and diverse fouling assemblages reported on ships elsewhere (Coutts 1999; Coutts and Taylor 2004; Davidson et al. 2006).

Similarly, rudders were not fouled extensively but were more frequently fouled and had significantly more fouling taxa than hulls. Organisms tended to occur along the trailing edges and at the articulations of rudders as opposed to the flat surfaces of the rudder faces that are subjected to high water flow. Fouling of ships' rudders in New Zealand (all ship categories) extended to $>$40% of the surface area sampled (Coutts and Taylor 2004), but percentage cover was low ($<$5%) on rudders sampled in Oakland because organisms were concentrated on the edges and within interstices. Likewise, organisms on stern tubes occurred primarily within small heterogeneous niche areas such as the articulation near the base of the propeller rather than along the length of the propeller shaft itself. These occurrences highlighted not only the importance of niche areas for fouling accumulation on ships, but that flat surfaces within these areas (rudders and running gears) were less important for biota than their recesses or 'nooks-and-crannies'. Mussel aggregations in the latter areas were particularly notable, and acted as 'microhabitat engineers' which increased the diversity of fouling assemblages by providing a matrix that other species could inhabit, especially mobile organisms that might not otherwise be associated with ships.

Factors associated with fouling accumulation

One vessel surveyed in Oakland (vessel r10) was a clear outlier in terms of the extent of fouling, and provided a stark contrast in important characteristics with all other vessels sampled. Although the extent of fouling on hulls for other ships sampled was in the range of square centimeters, vessel r10 had fouling cover extending at least two orders of magnitude higher than this (tens to hundreds of square meters). It was the only vessel sampled that had $>$1% of its available WSA covered in fouling organisms. It was sampled 26 months after dry docking (the mid range of all ships sampled) and had port durations typical of port visits for this ship type. It traveled at much slower speeds than other vessels (15 knots *vs* 21–24 knots) and its voyage route and voyage history differed greatly from those of the other ships. Prior to its short-sea shipping route on the US Pacific Coast, and subsequent to its last dry docking, vessel r10 worked among the Caribbean Islands where fouling accumulation and retention was probably higher than on the faster ocean-traversing ships sampled. Other studies have shown that vessels regularly traveling shorter distances are more likely to accumulate and retain fouling than those crossing vast expanses of latitude and longitude (Visscher 1928; Skerman 1960; Coutts and Taylor 2004). The present study allows only limited comparisons of oceanic *vs* regional voyages (21 *vs* 1 vessel), but this odd-ship-out suggested that recent voyage history and slower speeds were important determinants of its elevated extent of fouling.

Another recent study also used an outlier among sampled vessels to highlight the potential role of different hull coatings on the accumulation of fouling. Mineur et al. (2007) sampled algal fouling on 22 ships at a Mediterranean port and one vessel had 18 species while all others had between 2 and 8 species. This outlying ship used a non-biocidal AF paint, a unique characteristic among all vessels sampled. (This ship was also the only non-cargo vessel, which may have played an overlooked role in its accumulation of algal taxa.) In the present study, three vessels reported using non-biocidal coatings, but the richness and extent of fouling did not differ significantly from those that used biocidal AF paints, including those that had remnants of tin-based systems. The importance of the transition from banned, but highly effective, tin-based paints to copper and non-biocidal coatings is likely to impact organism settlement and retention, perhaps in such a significant way as to cause a major shift in shipping-related species transfers (Nehring 2001; Fofonoff et al. 2003). However, few empirical data exist to adequately evaluate the effect of such shifts in hull coatings on fouling and the risk of invasion.

Dry docking history clearly affects the occurrence and extent of fouling. Despite differences in voyage routes and coating types among vessels, a significant positive relationship between richness of taxa and time out of dry dock (age of paint) was present for vessels sampled in Oakland. A similar positive relationship was found for ships sampled in Tasmania (Coutts 1999). Regulations regarding the frequency of dry dock inspections distinguish between old vessels (<36 months) and new ones (up to 60 months) (International Maritime Organization 2004b). However, such regulations are based upon ship performance and safety, and not on fouling from an invasion risk perspective, which may yield different timetables.

Duration since dry docking is one of two metrics of immersion time relevant to fouling accumulation on ships that works over a time scale of months to years. The other metric, port duration, works over shorter temporal scales of hours to days. Several studies have highlighted the importance of immersion time for fouling accumulation and have shown that organism settlement in flow conditions (eg while vessels are underway) is restricted (Doochin and Walton-Smith 1951; Crisp 1955; Railkin 2003). Because containerships have shorter port durations compared to some other ship types (eg bulkers, general cargo), the opportunity for organism settlement in port is lower for this ship type. No significant difference was found in the accumulation of functional group richness over time between Oakland containerships and Tasmania ships (mainly bulkers). Comparisons of extent between studies, however, suggested that the percentage cover of fouling was lower on containerships (the present study) than other vessel types (Coutts 1999).

While ship type differences (port durations and vessel speeds) probably contribute to the extent of differences in fouling among ships, many additional variables also play a role. Vessel age, size, configuration (complexity of surfaces), voyage speeds and durations, previous source ports, voyage routes, destination ports and seasonality contribute to fouling transfers on ships (Minchin and Gollasch 2003; Godwin 2005; Mineur et al. 2007). The hierarchy among all of these factors that contribute to hull-mediated species incursions is yet to be determined. Similarly, little is known about the effect of transit on the fitness of organisms transferred on hulls, or their reproductive status after voyages. Such under-representation of this initial (vector) stage of introductions is widespread in the bioinvasion literature (Puth and Post 2005). Filling these information gaps is required for more insightful modeling of invasion risk in coastal systems (Floerl et al. 2005). Several international, national and state agencies throughout the world are considering biosecurity risks from ship fouling (Takata et al. 2006), and improved understanding of the relative importance of factors that affect transfer dynamics and invasion outcomes are key to developing successful management options.

Containerization heralded a new era in maritime shipping; a new efficiency in cargo handling helped to reduce port durations, allowing ships to increase their profitability by spending a much higher percentage of their time underway. Prior to containerization, all ships spent high percentages (averaging 30%) of their time in port, with days at a time required to load and unload cargo (Vigarie 1999). Today, containerships spend <1 day and usually <12 h in port. Because of their higher speeds, short port durations and intermodal efficiency, they have come to dominate shipping port arrival statistics around the world. It is likely that these aspects of vessel behavior have had the effect of reducing fouling transfers on a per-ship basis. The role of containerships as ballast water vectors of NIS has been highlighted previously (Niimi 2004), although subsequent analyses of variation among ship types showed that containerships generally discharge less ballast water than most other vessel types on a per-ship basis (Verling et al. 2005). This study suggests that fouling accumulation on containerships may not be as extensive as other ship types with different characteristics (slower speeds and longer port durations). However, the collection of data relating to fouling lags behind its ballast water counterpart, and further data from the undersides of commercial ships are required for a better understanding of the differences between ship types and an overall evaluation of the vector's contribution to marine introductions.

Acknowledgements

We are grateful to the Port of Oakland, especially Jody Zaitlin and Phil Granger, for access and logistical assistance throughout the project. We very much appreciate all the terminal and shipping line operators, staff and agents for arranging access to vessels as well as participating ship operators for their cooperation and insight. We thank George Smith for planning and advice; Bill Morrison, Don Ockrassa and Kevin Nekinaken for diving expertise; Michael Wright and Underwater Resources Inc for ROV expertise; Christina Simkanin for assistance in the field; Maurya Falkner, Lynn Takata and Suzanne Gilmore for discussions and advice. We also thank three anonymous reviewers for comments and suggestions that improved the manuscript. The Port of Oakland and the California State Lands Commission funded this research.

References

Callow ME, Callow JA. 2002. Marine biofouling: a sticky problem. Biologist 48:1–5.

Carlton JT. 1985. Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. Oceanogr Mar Biol Annu Rev 23:313–371.

Carlton JT, Newman WH. 2009. Reply to Clare and Høeg 2008. *Balanus amphitrite* or *Amphibalanus amphitrite*? A note on barnacle nomenclature. Biofouling 25:77–80.

Clarke KR, Gorley RN. 2001. PRIMER v5: User manual/tutorial. Plymouth, UK: PRIMER-E Ltd.

Coutts ADM. 1999. Hull fouling as a modern vector for marine biological invasions: investigation of merchant vessels visiting northern Tasmania [master's thesis]. Australian Maritime College, Launceston, Australia.

Coutts ADM, Taylor MD. 2004. A preliminary investigation of biosecurity risks associated with biofouling on merchant vessels in New Zealand. NZ J Mar Freshwater Res 38:215–229.

Crisp DJ. 1955. The behaviour of barnacle cyprids in relation to water movement over a surface. J Exp Biol 32:569–590.

Davidson I, Sytsma M, Ruiz G. 2006. Preliminary investigations of biofouling of ships' hulls: non-indigenous species investigations in the Columbia River. Groton (CT): US Coast Guard Research & Development Center. p. 1–65.

Doochin H, Walton-Smith FG. 1951. Marine boring and fouling in relation to velocity of water currents. Bull Mar Sci Gulf Caribb 1:196–208.

Eldredge LG, Carlton JT. 2002. Hawaiian marine bioinvasions: a preliminary assessment. Pac Sci 56:211–212.

Endresen Ø, Behrens HL, Brynestad S, Andersen AB, Skjong R. 2004. Challenges in global ballast water management. Mar Pollut Bull 48:615–623.

Endresen Ø, Sørgård E, Sundet JK, Dalsøren SB, Isaksen ISA, Berglen TF, Gravir G. 2003. Emission from international sea transportation and environmental impact. J. Geophys Res 108:1401–1422.

Entec International. 2005. Ship emissions: assignment, abatement and market-based instruments. Report to the European Commission, Directorate General Environment. Brussels, Belgium.

Falkner M, Takata L, Gilmore S, Dobroski N. 2007. 2007 biennial report on the California marine invasive species program. Sacramento (CA): California State Lands Commission, Marine Facilities Division.

Farrapeira CMR, Oliveira Marrocos de Melo AV, Barbosa DF, Euzebio da Silva KM.. 2007. Ship hull fouling in the port of Recife, Pernambuco. Braz J Oceanogr 55:207–221.

Floerl O, Inglis GJ, Hayden BJ. 2005. A risk-based predictive tool to prevent accidental introductions of nonindigenous marine species. Environ Manage 3 5:765–778.

Fofonoff PW, Ruiz GM, Steves B, Carlton JT. 2003. Invasive species: vectors and management strategies. In: Ruiz GM, Carlton JT, editors. In ships or on ships? Mechanisms of transfer and invasion for nonnative species to the coasts of North America. Washington DC: Island Press. p. 152–182.

Godwin LS. 2003. Hull fouling of maritime vessels as a pathway for marine species invasions to the Hawaiian Islands. Biofouling 19:123–131.

Godwin LS. 2005. Hull fouling as a mechanism for marine invasive species introductions. Proceedings of a workshop on current issues and potential management strategies; Feb 12–13 2004, Honolulu, Hawaii: Bishop Museum. p. 1–54.

Gollasch S. 2002. The importance of ship hull fouling as a vector of species introductions into the North Sea. Biofouling 18:105–121.

Gollasch S. 2006. Overview on introduced aquatic species in European navigational and adjacent waters. Helgol Mar Res 60:84–89.

Hewitt CL, Gollasch S, Minchin D. 2009. Biological invasions in marine ecosystems. In: Rilov G, Crooks JA, editors. The vessel as a vector – biofouling, ballast water and sediments. Berlin (Heidelberg): Springer-Verlag. p. 117–131.

Hewitt CL, Campbell ML, Thresher RE, Martin RB, Boyd S, Cohen BF, Currie DR, Gomon MF, Keough MJ, Lewis JA, et al. 2004. Introduced and cryptogenic species in Port Phillip Bay, Victoria, Australia. Mar Biol 144: 183–202.

International Maritime Organization. 1998. Regulations for the prevention of air pollution from ships and NOX technical code. Annex VI of MARPOL 73/78. London: International Maritime Organization.

International Maritime Organization. 2004a. International convention for the control and management of ships' ballast water and sediments. London: International Maritime Organization.

International Maritime Organization. 2004b. Revised survey guidelines under the harmonized system of survey and certification. London: International Maritime Organization.

Kite-Powell HL, Hoagland P. 2002. Economic aspects of right whale ship strike management measures. Report to the National Oceanic and Atmospheric Administration/National Marine Fisheries Service.

Laist DW, Knowlton AR, Mead JG, Collet AS, Podesta M. 2001. Collisions between ships and whales. Mar Mammal Sci 17:35–75.

Lewis EV. 1988. Principles of naval architecture. Jersey City (NJ): The Society of Naval Architects and Engineers.

Minchin D, Gollasch S. 2003. Fouling and ships hulls: how changing circumstances and spawning events may result in the spread of exotic species. Biofouling 19:111–122.

Mineur F, Johnson MP, Maggs CA, Stegenga H. 2007. Hull fouling on commercial ships as a vector of macroalgal introduction. Mar Biol 151:1299–1307.

Minton MS, Verling E, Miller AW, Ruiz GM. 2005. Reducing propagule supply and coastal invasions *via* ships: effects of emerging strategies. Front Ecol Environ 3:304–308.

Nehring S. 2001. After the TBT era: alternative antifouling paints and their ecological risks. Senckenb Marit 3:341–351.

Niimi AJ. 2004. Role of container vessels in the introduction of exotic species. Mar Pollut Bull 49:778–782.

Port of Oakland [Internet]. 2007. March 2007 Press release. Oakland (CA): Oakland sea port achieves record volume in 2006 [cited 2008 Jul 1]. Available from http://www.portofoakland.com/newsroom/pressrel/view.asp?id = 54

Puth LM, Post DM. 2005. Studying invasion: have we missed the boat? Ecol Lett 8:715–721.

Railkin AI. 2003. Marine biofouling: colonization processes and defenses. Florida: CRC Press.

Rodrigue J-P, Comtois C, Slack B [Internet]. 2006. Hofstra University, Department of Economics & Geography (NY): The geography of transport systems [cited 2008 Dec 1]. Available from: http://people.hofstra.edu/geotrans

Ruiz GM, Fofonoff PW, Carlton JT, Wonham MJ, Hines AH. 2000. Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. Ann Rev Ecol Sys 31:481–531.

Skerman T. 1960. Ship fouling in New Zealand waters: a survey of marine fouling organisms from vessels of the coastal and overseas trade. NZ J Sci 3:620–648.

Takata L, Falkner M, Gilmore S. 2006. Commercial vessel fouling in California: analysis, evaluation, and recommendations to reduce nonindigenous species release from the non-ballast water vector. Sacramento (CA): California State Lands Commission, Marine Facilities Division.

Van Maanen JD, Van Oossanen P. 1988. Principles of naval architecture, Vol. II. Jersey City (NJ): The Society of Naval Architects and Engineers. p. 1–93.

Verling E, Ruiz GM, Smith LD, Galil B, Miller AW, Murphy K. 2005. Supply-side invasion ecology: characterizing propagule pressure in coastal ecosystems. Proc R Soc B – Biol Sci 272:1249–1256.

Vigarie A. 1999. From break-bulk to containers: the transformation of general cargo handling and trade. Geojournal 48:3–7.

Visscher JP. 1928. Nature and extent of fouling of ships' bottoms. Bull Bur Fish 43:193–252.

Ward-Geiger LI, Silber GK, Baumstark RD, Pulfer TL. 2005. Characterization of ship traffic in Right Whale critical habitat. Coast Manage 33:263–278.